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Integrated Stability Assessment of Mine Tailings under Static and Seismic Conditions: Application of Limit Equilibrium Methods and Eurocode 7 to the Auzelles Site (France)

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ABSTRACT

The instability of mine tailings represents a major environmental and geotechnical challenge, particularly due to the risk of slope failure and contamination of surrounding watercourses. At the Auzelles site (Auvergne, France), the absence of prior stability assessment combined with steep natural slopes (35°–40°) constitutes a critical factor of instability. This study aims to evaluate the stability of slag heap 1 by analyzing the influence of slope geometry under both static and pseudo-static conditions. The methodology is based on limit equilibrium analysis using Talren software, with the simplified Bishop method, in accordance with both the traditional approach and the EN1997-1 Eurocode 7 framework. Two representative cross-sections were analyzed before and after earthworks. The analysis assumes free-draining tailings conditions, with no pore water pressure considered. The results show that the initial state of the slopes is unstable, with safety factors of 1.07 under static conditions, 0.89 under pseudo-static conditions, and 0.78 using the Eurocode approach, indicating a high risk of failure. After slope regrading to 27°, a significant improvement in stability is observed. The safety factors increase to 1.42–1.44 under static conditions, 1.11–1.15 under pseudo-static conditions, and 1.03–1.05 using the Eurocode approach, satisfying the required stability criteria. These results demonstrate that slope geometry is the primary controlling factor of stability at the site, and that reprofiling significantly enhances safety conditions. The study confirms

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the effectiveness of combining traditional and normative approaches for reliable stability assessment and highlights the importance of considering both static and seismic conditions in the long-term management of tailings storage facilities.
Keywords: Mine Tailings; Slope Stability; Limit Equilibrium Method; Eurocode 7; Pseudo-Static Analysis

1. Introduction

The mining industry produces large quantities of waste, often stored on the surface. Mine tailings, also known as tailings, concentrates, are finely ground materials stored on extraction sites [1]. They are mixtures of crushed rock and processing liquids from mills, washing plants or concentrators, left over after the extraction of precious metals, minerals, mineral fuels or coal [2]. According to Coulibaly [3], a large proportion of these residues is stored on the surface as pulp in ponds surrounded by dikes. However, these dykes are prone to failure, and tailings leakage can result in considerable material damage and major environmental impacts. Environmental pollution resulting from mine tailings is a complex challenge for mining companies [4]. The instability of some of these tailings represents an environmental risk that must be taken into account both during operation and after mine closure [4].

As highlighted by Whajah et al. [5], tailings storage facilities represent one of the most critical components of mining operations due to their potential for catastrophic failure driven by factors such as seismic loading, seepage, extreme weather conditions, and poor operational practices. Similarly, Clareti Pereira [6] emphasizes that the stability of tailings storage facilities has evolved into a multidisciplinary challenge involving not only geotechnical properties but also monitoring systems, governance, and real-time data integration.

Unfortunately, this environmental risk associated with the instability of tailings at the Auzelles site was not taken into account either during or after mining.

Seepage processes are widely recognized as one of the main causes of tailings dam failure, accounting for approximately 20% to 35% of global accidents [7], highlighting the importance of accurately controlling pore water pressure and phreatic levels. In this context, the hydrological state of tailings, particularly the water table position and the degree of saturation, plays a key role in controlling their long-term behavior [8].

The Auzelles mine site, a former silver-lead mine that operated underground until 1901 [9], covers an area of around 4.5 ha and is currently home to around 150,000 m^3 of material [10]. These materials are residues from ore processing carried out on site by the washing plant and are responsible for water pollution downstream from the site [11].

In the specific case of the Auzelles site, the geometric characteristics of the slopes, with natural inclinations ranging from 35° to 40°, constitute a significant aggravating factor for instability, particularly in a context where no prior stability assessment had been carried out before this study.

Previous studies have shown that seepage conditions, including the phreatic line and pore water pressure distribution, significantly influence dam stability and can be improved through drainage techniques or slope reconfiguration [12,13]. Conversely, factors such as material stratification or physico-chemical interactions may degrade hydromechanical properties and increase instability risks [14,15].

From a mechanical perspective, mine tailings may exhibit behavior highly sensitive to loading conditions, particularly under seismic actions, which requires analysis under both static and pseudo-static conditions to better represent real stability conditions [16,17].

Furthermore, several studies have shown that conventional approaches may lead to an overestimation of the safety factor if pore water pressures or simplifying assumptions are not properly considered [18,19]. In addition, transient conditions and the evolution of hydric states can play a critical role in the overall stability of tailings deposits.

In this context, the combined use of traditional calculation methods and normative approaches such as Eurocode 7 improves the reliability of stability assessment and better accounts for uncertainties related to geotechnical parameters and loading conditions [20].

The aim of this article is to study the long-term stability of mine tailings (terril 1) in order to prevent landslides that could contaminate water downstream from the site for several hundred years. More specifically, the paper seeks to achieve the following objectives: analyze the stability of the tailings in their current state (before earthworks) with slopes varying from 35 to 40°, and after earthworks (27° slope) using the traditional method, under static and pseudo-static conditions (taking into account seismic stresses), as well as according to the EN1997-1 Approach of Eurocode 7.

1.1. Geography

The site is located in the Auvergne-Rhône-Alpes region, in the Puy-de-Dôme département, some forty kilometers southeast of Clermont-Ferrand, in the commune of Auzelles. It lies to the north-west of the Livradois mountains. It is characterized by a rugged topography, with altitudes ranging from 650 to 700 m NGF (Nivellement Général de la France).

The repository lies below the D 996 departmental road and is bordered on its northern and western sides by the Miodet stream (**Figure 1**). On the south-western side, it is bordered by an unnamed temporary stream, named "ruisseau Molette" in this study (as it originates from the hamlet of La Molette).

1.2. Climate

Referring to the umbrothermal diagram for Clermont-Ferrand (Aulnat station) covering the period from 1993 to 2023 (**Figure 2**), we can see that the precipitation histogram is systematically above the temperature curve throughout the year. This pattern reveals that there is a single wet period and no identifiable dry period throughout the year.

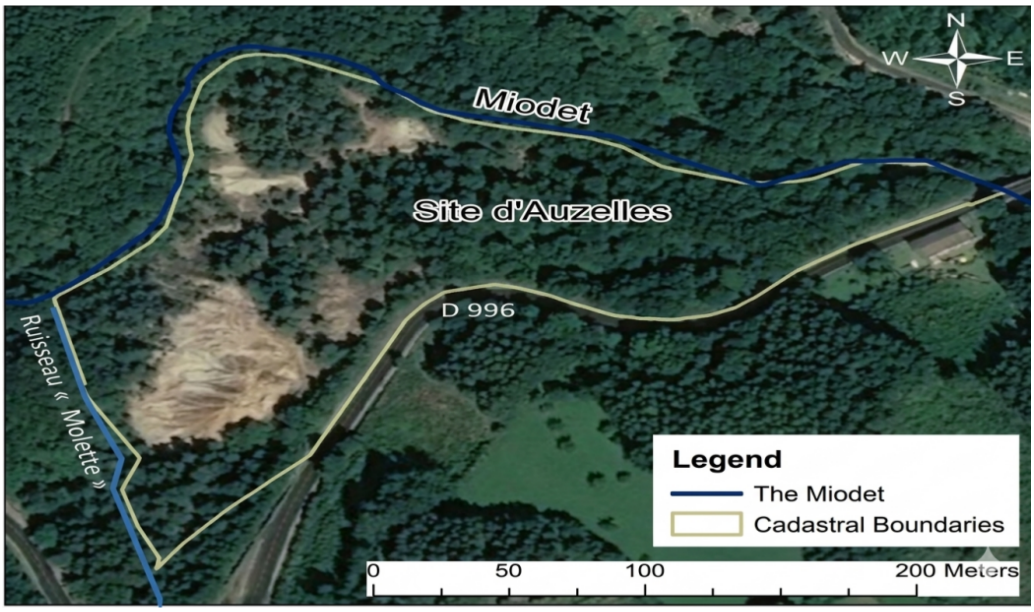

Figure 1. Site plan of the Molette deposit in the commune of Auzelles [11].

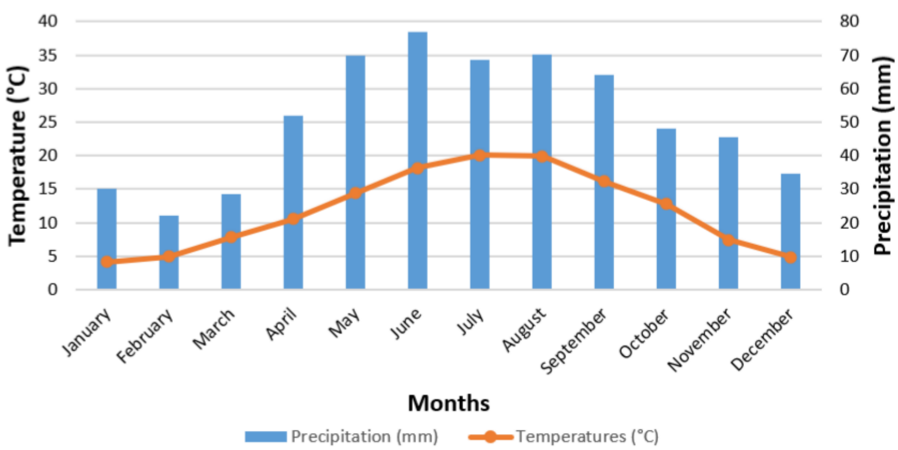

Figure 2. Gaussen umbrothermal diagram for Clermont-Ferrand-Aulnat station (1993/2022).

The current climate in the study region (Clermont-Ferrand) is intermediate between oceanic and continental, but with continental influences due to the proximity of the Chaîne des Puys (a chain of volcanoes running north–south, with the highest peak reaching 1,465 m). It is semi-continental, fairly cold in winter and fairly hot in summer.

1.3. Hydrology and Hydrogeology

From a hydrological point of view, the study area, located between St-Eloy-la-Glacière and the Miodet reservoir, has a fairly dense hydrographic network. It is crossed from south to north by the Miodet stream, a tributary of the Dore River, which flows some fifteen kilometers to the east of Auzelles.

According to Groupement d'Intérêt Public (GEODERIS)[10], from a hydrogeological point of view, groundwater is present in three types of hydrogeological compartments in the area. These are: loose altered horizons (weathered materials), fissured altered horizons and unaltered basement.

1.4. Geology

Geologically speaking, the study area consists of a crystalline metamorphic and granitic basement (**Figure 3**). The site lies at the contact between the metamorphic formations to the southwest (migmatitic gneiss) and the Saint-Dier granite to the northeast (the contact between the formations broadly follows the Miodet stream on a regional scale).

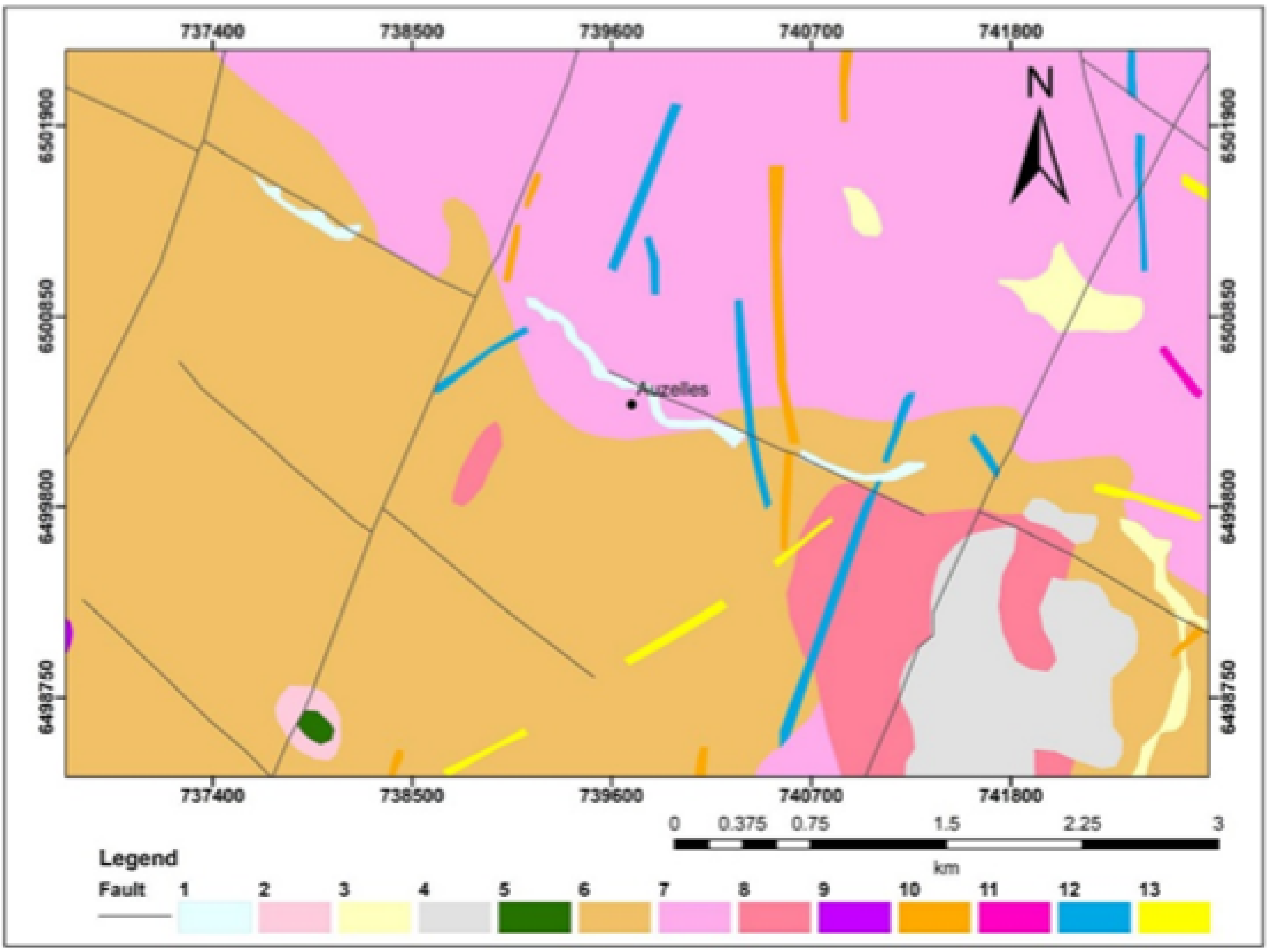

Figure 3. Geological map of the study area[21].

Note: Legend: 1: Alluvial deposits from rivers. 2: Various volcanic rocks (pyroclastics, basalt scoria, basalts, rhyolites, picrites, etc.). 3: Slope and valley floor colluvium. 4: Plutonic and/or metamorphic and/or volcanic rocks. 5: Miocene volcanism (ankaramites, basalts). 6: Upper unit of gneiss (granitoid diatexites-anatexites with biotite and cordierite). 7: Hercynian basement (calco-alkaline granites with biotite and cordierite from Saint-Dier). 8: Hercynian basement (leucocratic porphyroid granite from the Bois de Sérat). 9: Hercynian basement (leucogranites with fine grains and two micas). 10: Microgranites to microleucogranites, porphyritic, in small masses or veins. 11: Pegmatites, aplo-pegmatites, in veins or small bodies. 12: Lamprophyres, microdiorites, quartz microdiorites; in veins. 13: Quartz veins.

2. Methodology

2.1. Service Life and Geotechnical Category

Geotechnical design is based on the service life and geotechnical category in accordance with Eurocode 7 (NF EN 1997-1), with the project classified in category 5 corresponding to a design life of 100 years (**Table 1**).

The geotechnical category depends on site complexity and failure consequences (Consequence Class 1–3 or CC1–CC3); in this study, the potential impact is mainly environmental (Miodet stream), leading to a classification of CC2 (Consequence Class 2) and thus geotechnical category 2.

2.2. Calculation Methodology

Stability calculations were carried out using Talren version 5 software, which is specifically designed to assess slope and embankment stability. This software is based on limit equilibrium methods (LEM), which remain widely used in geotechnical engineering due to their robustness and simplicity [16,22]. For the purposes of this study, the calculation model selected was Bishop's, adapted for two-dimensional circular failure surfaces. The simplified Bishop method is one of the most widely accepted methods for slope stability analysis due to its accuracy and efficiency [14,23]. The safety factor (SF), considered constant along the fracture surface, is defined as the ratio between the maximum shear stress and the mobilized shear stress. It represents the ratio between available shear strength and mobilized shear stress along the potential failure surface. The mobilizable shear stress depends essentially on the intrinsic characteristics of the residues, notably the angle of internal friction and cohesion, while destabilizing forces include self-weight, pore pressure, and external loads. This formulation is consistent with classical soil mechanics and slope stability theory [24].

For each slope configuration studied, the software evaluates a wide range of potential failure surfaces, and the minimum safety factor (FSmin) corresponds to the most critical stability condition.

Two equivalent approaches were used:

- **Calculation 1: Traditional method**, where the weighting coefficients applied to the geotechnical parameters are equal to 1. This approach requires a safety factor FS > 1.3 under static conditions and FS > 1 under pseudo-static conditions, which are standard criteria in engineering practice [25].
- **Calculation 2: Eurocode 7 approach (EN 1997-1)**, using Design Approach 3 (A2 + M2 + R3), recommended for slope stability problems [26,27]. In this case, the objective is to satisfy ultimate limit state (GEO) conditions with FS ≥ 1.0.

Table 1. Indicative service life of structures.

Project Useful Life	Indicative Useful Life of Years	Examples of Civil Engineering Projects
1	10	Temporary structures
2	25	Replaceable structural elements
3	25	Agricultural and similar structures
4	50	Standard civil engineering structures and buildings
5	100	Other civil engineering structures, bridges

2.3. Geomechanical Characteristics of Materials

In view of the high degree of uniformity in cohesion and friction angle values observed both for the tailings samples from tip 1 and for those from the base of tip 1, we will define only three types of material for the stability calculations: base of slag heap 1, heap 1 residue in place, and reworked slag heap 1 residue (in situ slag heap 1 residue removed for backfilling). This simplification is adopted to ensure a representative and manageable geotechnical model for stability analysis [22].

The mechanical characteristics of the various materials taken into account in the stability calculations are summarized in **Table 2**. The values of cohesion, angle of friction and density used in the stability calculations correspond to the average of the parameters of the samples considered for each type of material.

For in-place tailings, laboratory results indicate zero cohesion. However, considering the observed slope angles

(35°–40°), a strictly zero cohesion may not fully represent in-situ stability conditions. Therefore, a back-analysis was performed, leading to the adoption of a cohesion value of 2 kPa, which allows a safety factor of 1 (limit equilibrium) to be achieved under current topography, as shown in **Figure 4**. This back-analysis approach enables calibration of shear strength parameters under in-situ conditions [24]. This cohesion value was therefore used in the stability analysis for in-place tailings.

Table 2. Mechanical characteristics of materials used in calculations.

Soil Type	Subgrade	Reworked Residue	In-Place Residue
Samples considered	S-01, S-02, S-03	R-01, R-02, R-03	R-01, R-02, R-03
Density (kN/m^3)	15.5	16.3	16.3
Effective cohesion (kPa)	0.0	0	0
Effective angle of friction (°)	30	28	28

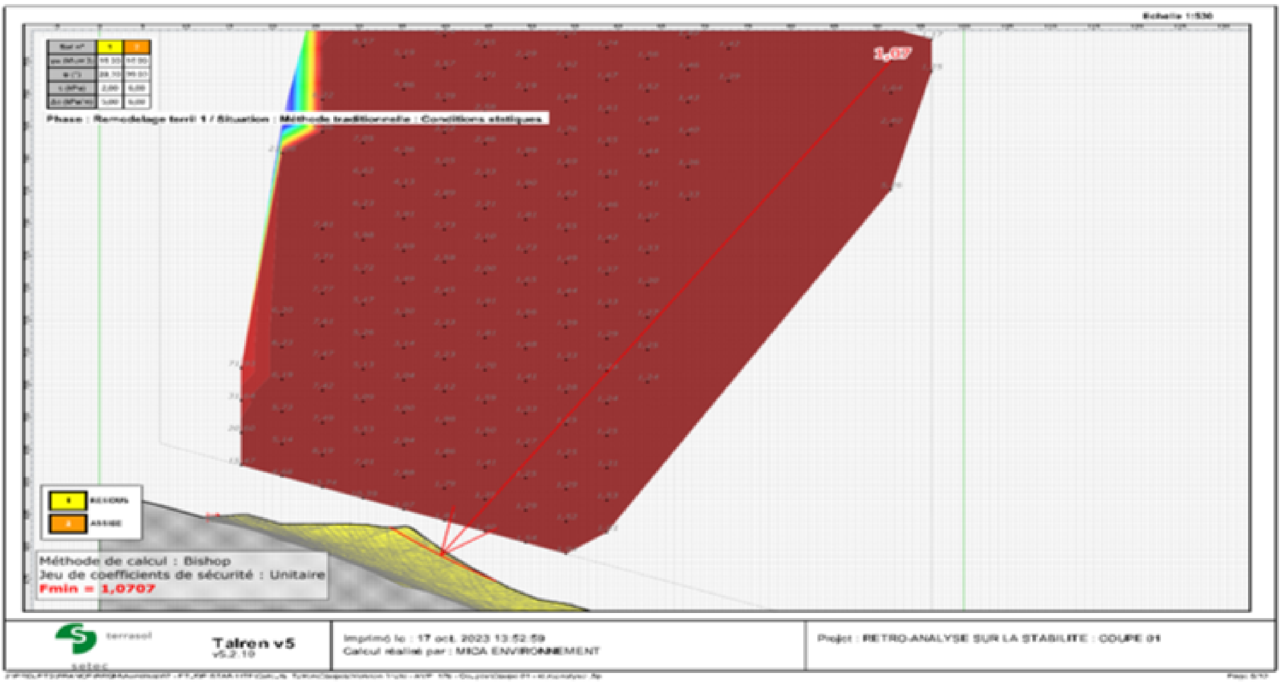

Figure 4. Back-analysis under static conditions (current topography).

Note: This figure shows the results of the back-analysis under static conditions using the traditional approach based on the Bishop method with unit coefficients. It presents the failure surface and the safety factor, with F_{min} = 1.07, indicating a marginally stable slope.

2.4. Calculation Assumptions

2.4.1. Seismic Conditions

Since October 22, 2010, France has implemented a seismic zoning system dividing the territory into five zones of increasing seismicity (decrees No. 2010–1254 and No. 2010–1255), defining risk prevention and design rules for structures in accordance with Eurocode 8 (**Figure 5**).

Structures are classified into four importance categories (I to IV) according to Article R.563-3 of the French Environment Code, which define the level of seismic design requirements. Mine tailings can be classified in importance category II, corresponding to an importance coefficient γ_1 equal to 1, as presented in **Table 3**.

In a pseudo-static stability analysis, the effect of an earthquake is modeled by two inertial forces, horizontal towards the slope and vertical upwards or downwards, the moduli of which are proportional to the weight of the volume of material loaded, via the seismic parameters: the horizontal acceleration coefficient (K_h) and the vertical acceleration coefficient (K_v).

According to Eurocode 8, the horizontal acceleration coefficient created by an earthquake is determined by the equation:

$$K_h = 0.5 \times \frac{a_g}{g} \times S \quad (1)$$

where a_g: estimated horizontal acceleration (m/s^2), g is the gravitational acceleration (m/s^2), and S is the soil amplification factor.

The design horizontal acceleration is calculated as $a_g = agr \times \gamma_1 = 1.1 \times 1 = 1.1$ m/s^2. According to Eurocode 8, the site corresponds to soil class E, with an amplification factor $S = 1.8$, as summarized in **Table 4**.

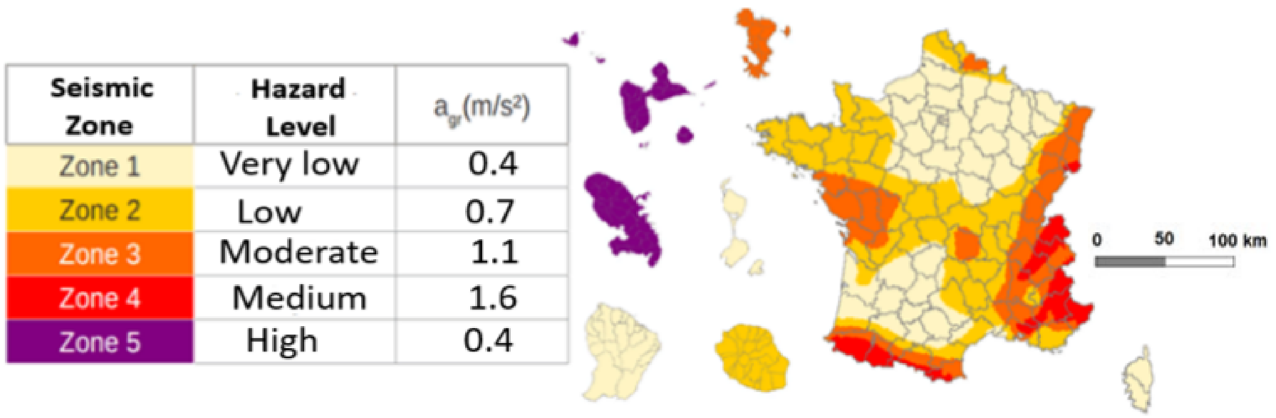

Figure 5. Seismic zoning of France.

Table 3. Importance categories for structures.

Categories of Importance	Description	γ_1
I	Minimal risk to people or socio-economic activity.	0.8
II	Medium risk for individuals.	1
III	High risk for people and/or their socio-economic importance.	1.2
IV	Operation of primary importance for civil security, defense or the maintenance of public order.	1.4

Table 4. Description of stratigraphic profile by soil class.

Soil Class	Description of Stratigraphic Profile	Characteristic Soil Parameter (S)	
		Seismicity Zones 1 to 4	Seismicity Zones 1 to 5
A	Rock or similar geological formation with a surface layer of at least 5 m of less resistant material.	1	1
B	Steep deposits of sand, gravel or over consolidated clay, at least several tens of meters thick, characterized by a progressive increase in mechanical properties with depth.	1.35	1.2
C	Deep deposits of medium-density sand, gravel or moderately stiff clay, with thicknesses from a few tens to several hundreds of meters.	1.5	1.15
D	Deposits of cohesionless soil of low to medium density (with or without soft cohesive layers) or comprising a majority of soft to firm cohesive soils.	1.6	1.35
E	Soil profile comprising a superficial layer of alluvium with shear-wave velocity (Vs) values of class C or D and a thickness of between approx. 5 m and 20 m, resting on a stiffer material with Vs > 800 m/s.	1.8	1.4

Substituting these values into the equation gives $K_h = 0.101$, while the vertical coefficient is taken as $K_v = \pm 0.5$ Kh, leading to $K_v = \pm 0.051$. These coefficients are used in the stability calculations under pseudo-static conditions.

2.4.2. Hydraulic Conditions

The measured permeability (5.5 × 10−5 m/s) indicates a draining material. No seepage was observed. Therefore, pore pressure effects were neglected, which is acceptable for free-draining tailings [12,28].

2.4.3. Surcharges

Given the absence of traffic or installations, no surcharges were considered. This simplifies boundary conditions without affecting stability results.

2.5. Stability Calculation Profiles

To ensure an accurate assessment of the project's overall stability, the most unfavorable cross-sections were selected. These sections were chosen by following the line of greatest slope and placing them perpendicular to the contour lines, as shown in **Figure 6**. This approach allows identification of the most critical stability conditions and ensures a representative analysis. The site profile, including tailings, bedrock and subsoil, is shown in **Figure 7**.

Figure 6. Cross-section plan for project stability calculations.

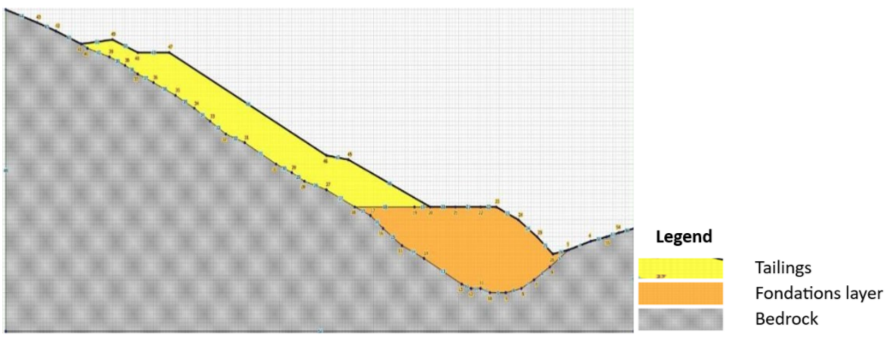

Figure 7. Section showing tailings and bedding soils.

3. Results

The stability calculation was carried out taking into account slopes inclined at 27°, which corresponds to an optimized slope angle improving stability conditions, as reported in previous studies [29].

The main objective was to achieve a minimum safety coefficient of 1.3 under static conditions, and a coefficient greater than 1 under pseudo-static conditions, in accordance with the Eurocodes. These criteria are widely used in geotechnical design to ensure long-term stability of tailings structures [30].

Calculations were carried out using a traditional method, where the weighting coefficients applied to the geotechnical parameters are all equal to 1. This approach is commonly used for preliminary stability assessments and provides a baseline for comparison with more advanced methods[16].

This methodical approach guarantees a thorough assessment of the project's stability, taking into account different scenarios and conditions. It also allows validation of results through comparison between static and pseudo-static conditions, which is essential for reliable design[31].

3.1. Stability Analysis before Earthworks (Natural Slope)

Stability analysis was initially carried out on slopes with a natural gradient of between 35° and 40°, prior to any remodeling. This approach enabled us to assess the stability of the site in its initial state, taking into account the natural characteristics of the terrain.

The results of this analysis provided crucial information on the stability of the site prior to any human intervention. They highlight that natural slopes with steep inclinations generally exhibit low safety factors, confirming observations from previous tailings stability studies[16].

3.1.1. Traditional Method

- **Static Conditions**

The factor of safety calculated under static conditions before earthworks is 1.07, as shown in the diagram below (**Figure 8**). This value is below the recommended threshold of 1.3, indicating insufficient stability under static conditions. This confirms that the natural slope does not meet long-term stability requirements, particularly for steep slopes where instability risks are higher[29].

- **Pseudo-Static Conditions**

According to **Figure 9**, the factor of safety calculated under pseudo-static conditions before earthworks is 0.89 for cut 1, indicating a significant decrease in stability due to dynamic loading effects, which is consistent with previous studies showing that seismic conditions reduce the factor of safety[32].

3.1.2. EN 1997-1 Eurocode 7 Approach

The safety factor of 0.78, calculated in accordance with Eurocodes prior to any earthworks, as shown in **Figure 10**, highlights a situation where the tailings do not meet the stability standards required to ensure their long-term safety. A value lower than 1 indicates a high probability of failure, which is consistent with Eurocode-based assessments for unstable slopes[30].

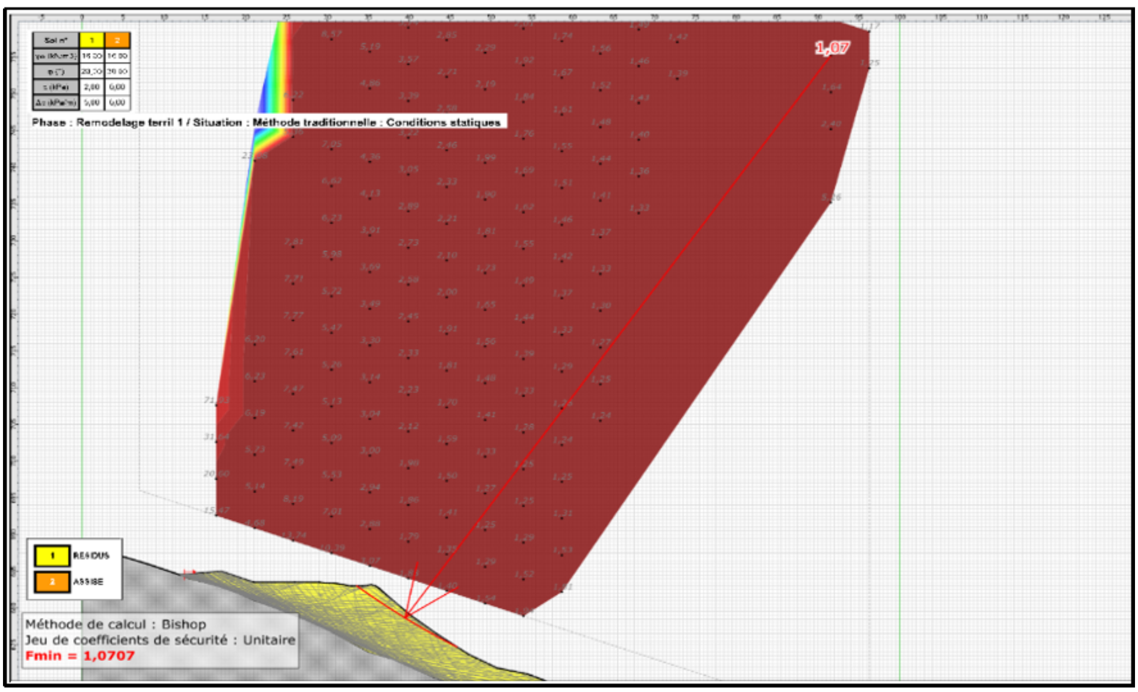

Figure 8. Stability results using the traditional method, static conditions (Section 01).

Note: Static condition analysis using the traditional approach, performed with the Bishop method and unit safety coefficients. The minimum safety factor is F_{min} = 1.07.

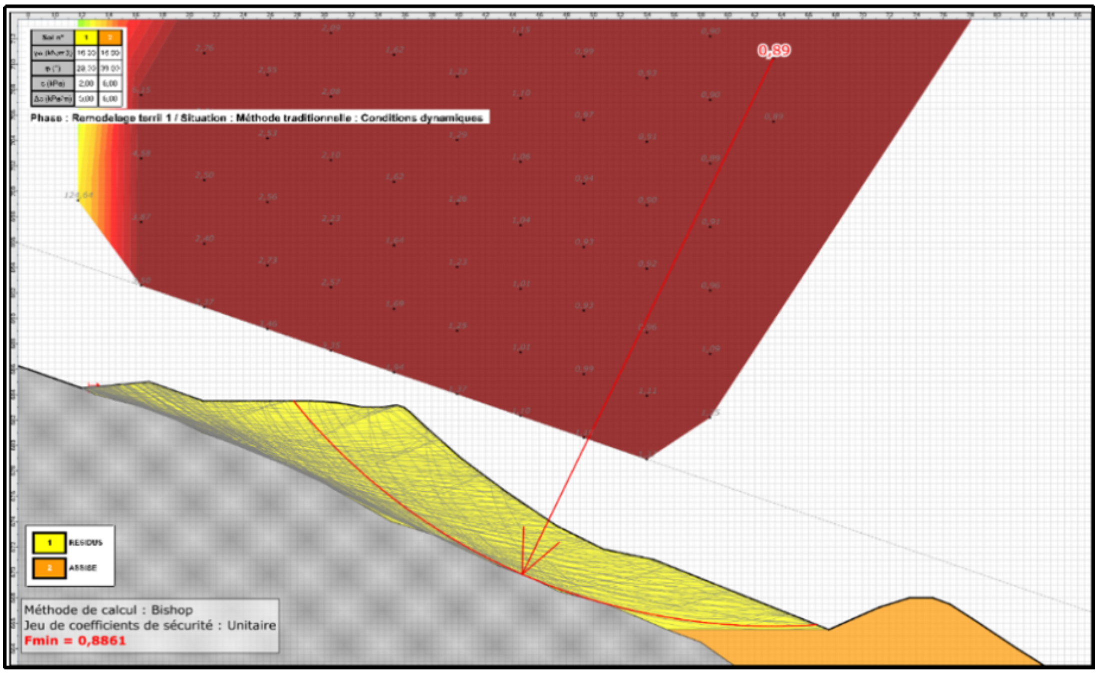

Figure 9. Stability results using traditional, pseudo-static methods (Section 01).

Note: Stability analysis carried out under dynamic conditions using the traditional approach, based on the Bishop method with unit safety coefficients. The minimum safety factor obtained is F_{min} = 0.88.

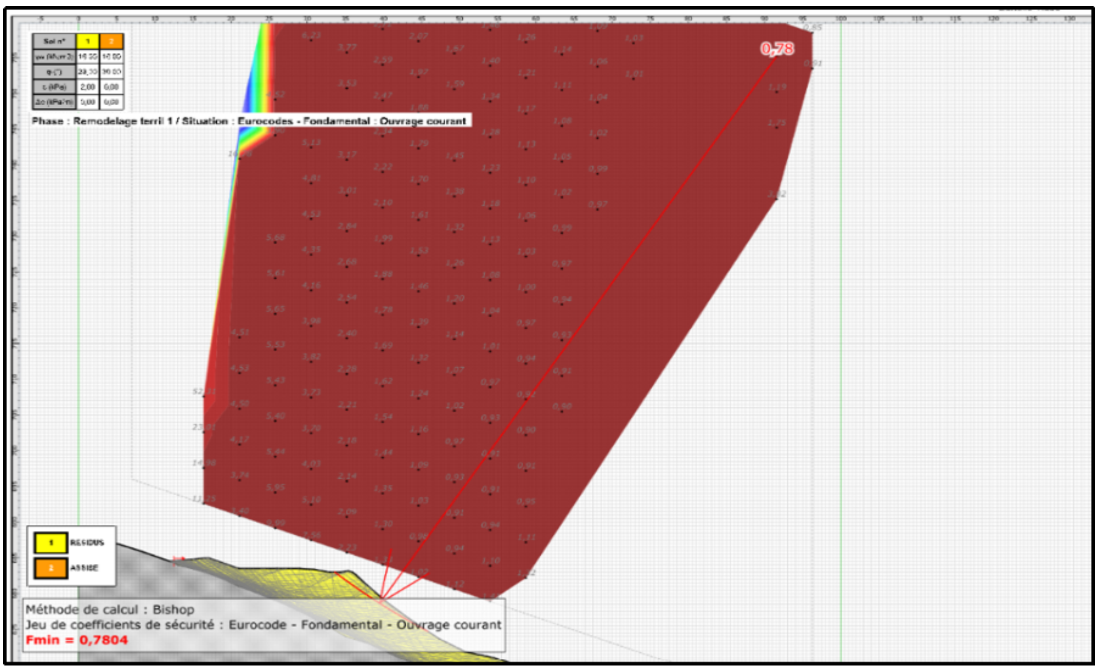

Figure 10. Stability results, Eurocodes approach (Section 01).

Note: Static condition analysis according to the Eurocode approach (fundamental case – standard structure), performed using the Bishop method. The minimum safety factor obtained is F_{min} = 0.78.

3.2. Stability Analysis after Earthworks

3.2.1. Traditional Method

In the traditional method, stability calculations were carried out taking into account both static and pseudo-static conditions. For the latter, the seismic acceleration coefficients selected are crucial for assessing the effect of seismic shocks on structural stability.

In this particular case, the seismic acceleration coefficients adopted are $K_h = 0.101$ and $K_v = -0.051$. These values are significant because they represent the worst case in terms of seismic acceleration. K_h corresponds to horizontal acceleration and K_v to vertical acceleration.

The use of these coefficients in pseudo-static calculations enables us to take into account the potential effects of seismic shocks on the stability of the structure. This approach is widely used in slope stability analysis to simulate dynamic loading conditions and evaluate their impact on safety factors [32].

- **Static Conditions**

According to **Figure 11**, the safety coefficient calculated under static conditions is 1.42 for Section 01. This value indicates that the objectives set in terms of long-term residue stability have been achieved. This improvement compared to the initial state demonstrates the effectiveness of earthworks in increasing slope stability, as also observed in similar studies [16].

This analysis highlights the fact that, under these specific static conditions, tailings stability is ensured with a satisfactory factor of safety. This means that the tailings slopes are able to withstand the forces applied without risk of failure or excessive slippage.

These results are consistent with previous studies showing that slope regrading and optimized geometry significantly increase stability [31].

The safety coefficient for Section 02, calculated under static conditions and displayed in **Figure 12**, is 1.44, exceeding the targets initially set for long-term tailings stability. The slightly higher value compared to Section 01 suggests a local influence of geometry or material distribution, which is commonly observed in slope stability analyses [18]. This analysis highlights the enhanced stability, even exceeding expectations, underlining the effectiveness of the safety measures implemented.

- **Pseudo-Static Conditions**

According to the results shown in **Figure 13**, the safety factor calculated under dynamic (pseudo-static) conditions for Section 01 is 1.11. This value indicates that the objectives set to guarantee long-term residue stability have been achieved. However, this value is lower than under static conditions, confirming that dynamic loading reduces slope stability due to additional inertial forces. This decrease in safety factor is consistent with previous studies where pseudo-static conditions led to a systematic reduction in stability [32].

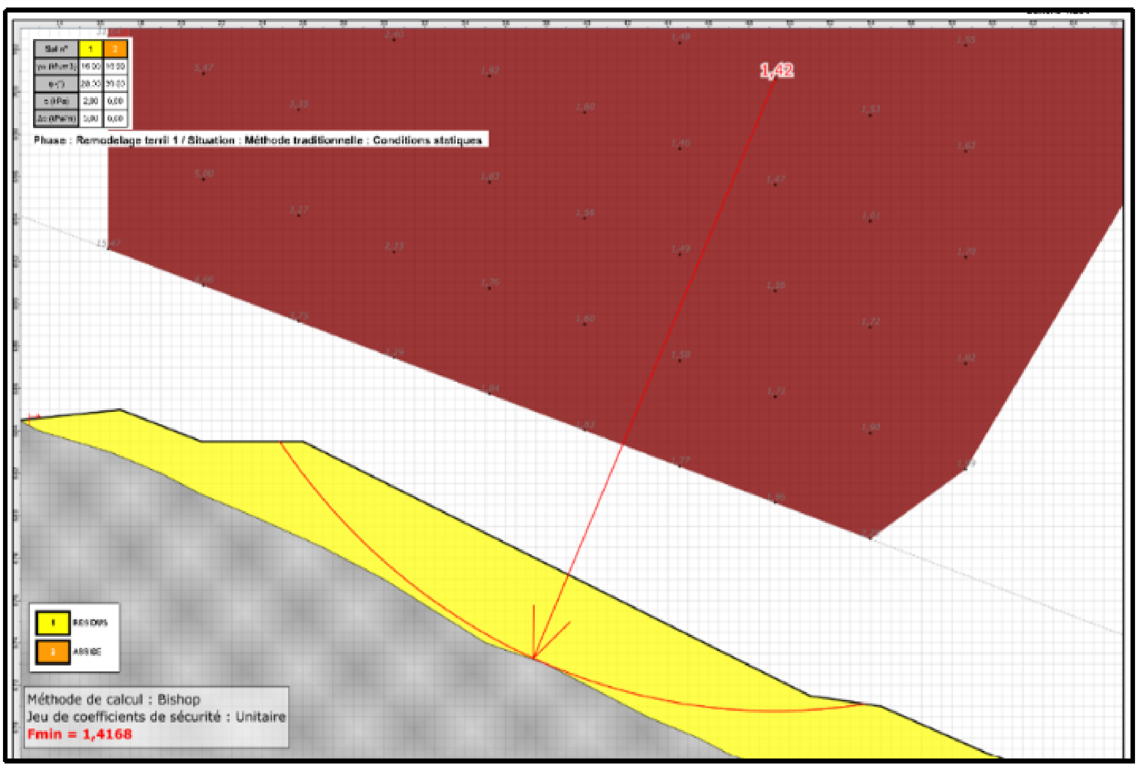

Figure 11. Conventional stability results, static conditions (Section 01).

Note: Static condition analysis using the traditional approach, performed with the Bishop method and unit safety coefficients. The minimum safety factor obtained is F_{min} = 1.42.

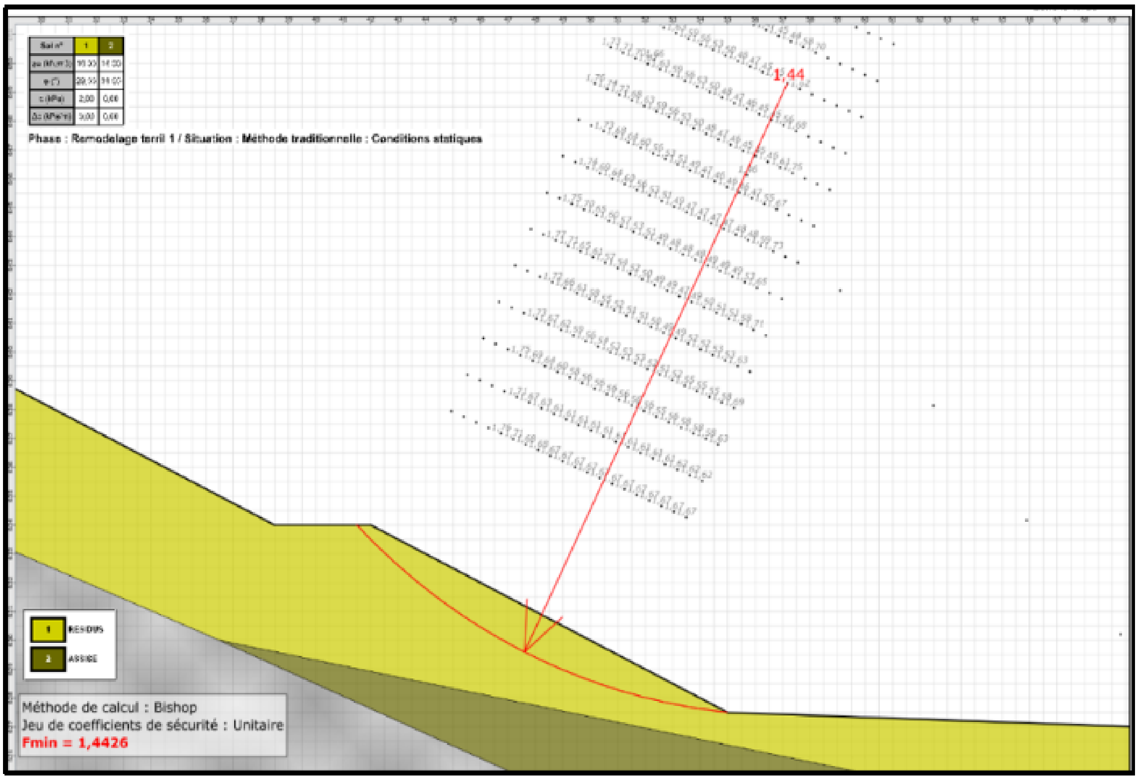

Figure 12. Stability results using the traditional method, static conditions (Section 02).

Note: Results of the stability analysis under static conditions using the traditional approach, based on the Bishop method with unit safety coefficients. The minimum safety factor is F_{min} = 1.44.

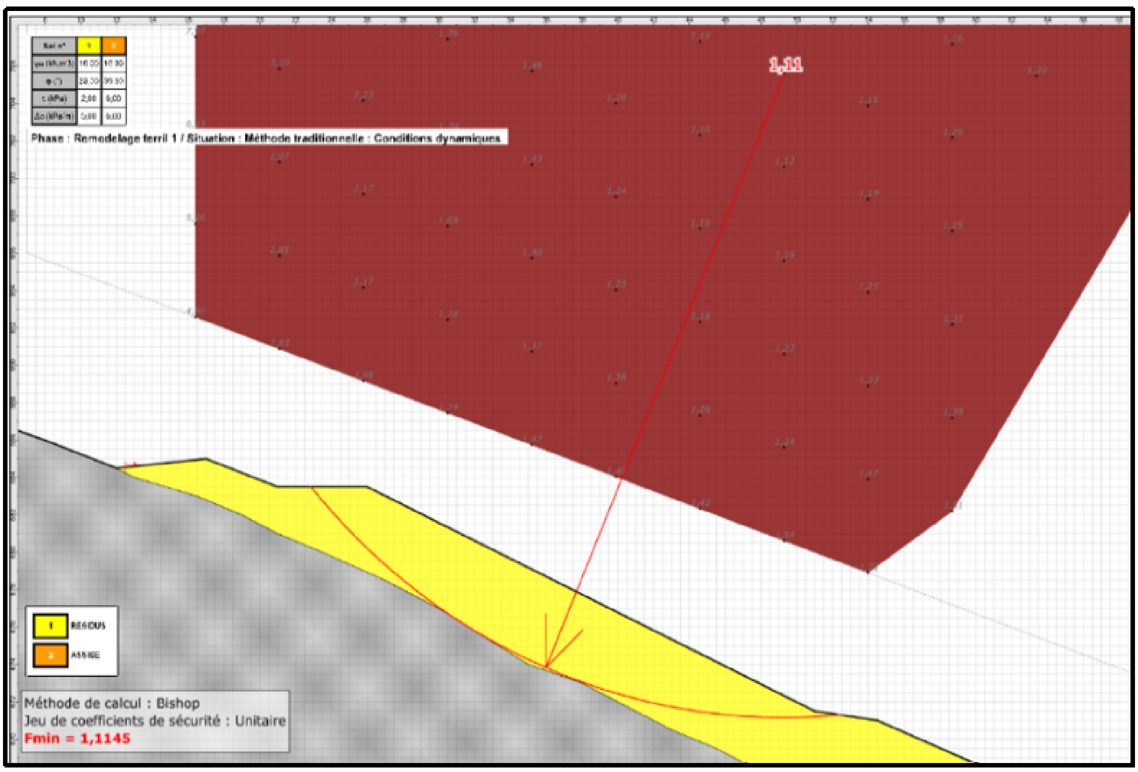

Figure 13. Stability results using traditional method, pseudo-static (Section 01).

Note: Stability analysis carried out under dynamic conditions using the traditional approach, based on the Bishop method with unit safety coefficients. The minimum safety factor obtained is F_{min} = 1.11.

According to the results shown in **Figure 14**, the safety coefficient calculated under dynamic conditions (pseudo-static) for Section 02 is 1.15. This value indicates that the residues meet the established long-term stability criteria. Although stability remains acceptable, the reduction compared to static conditions highlights the sensitivity of the slope to seismic effects [31].

3.2.2. EN 1997-1 Eurocode 7 Approach

Application of the EN 1997-1 Eurocode 7 method to calculate the safety factor for Section 01 gave a result of 1.03, as shown in **Figure 15**. This value, slightly above unity, indicates a limit equilibrium condition, which is typical of Eurocode-based design approaches aiming for conservative stability criteria [30]. Compliance with the criteria defined by this normative approach ensures that the tailings present no imminent risk of slippage or instability, thus ensuring the long-term safety of the structure.

The result obtained by applying the EN 1997-1 Eurocode 7 approach provides an accurate and robust assessment of the long-term stability of the residues. In this context, **Figure 16** shows the safety coefficient calculated specifically for Section 02, where this coefficient amounts to 1.05. The close values obtained for both sections confirm the consistency of the Eurocode approach and its reliability in evaluating slope stability [30]. This value indicates that the tailings are sufficiently stable to meet the stability criteria defined for the long-term project.

Table 5 summarizes the minimum safety factor results for the various situations along Sections 01 and 02.

Analyzing the results summarized in **Table 5**, it is clear that the minimum safety factors obtained under static conditions along cuts 01 and 02 are 1.42 and 1.44 respectively. These values far exceed the minimum safety threshold of 1.3, indicating adequate residue stability under these conditions.

What's more, even when considering pseudo-static conditions and using the Eurocodes-based approach, the minimum safety factors remain above 1 for both cuts. This means that, irrespective of the analysis method used, the results confirm satisfactory long-term residue stability.

These results demonstrate the robustness of the adopted methodology and are consistent with studies showing good agreement between different stability analysis methods (LEM vs. FEM) [16]. Furthermore, the convergence of results obtained from different approaches increases confidence in the reliability of the stability assessment [18].

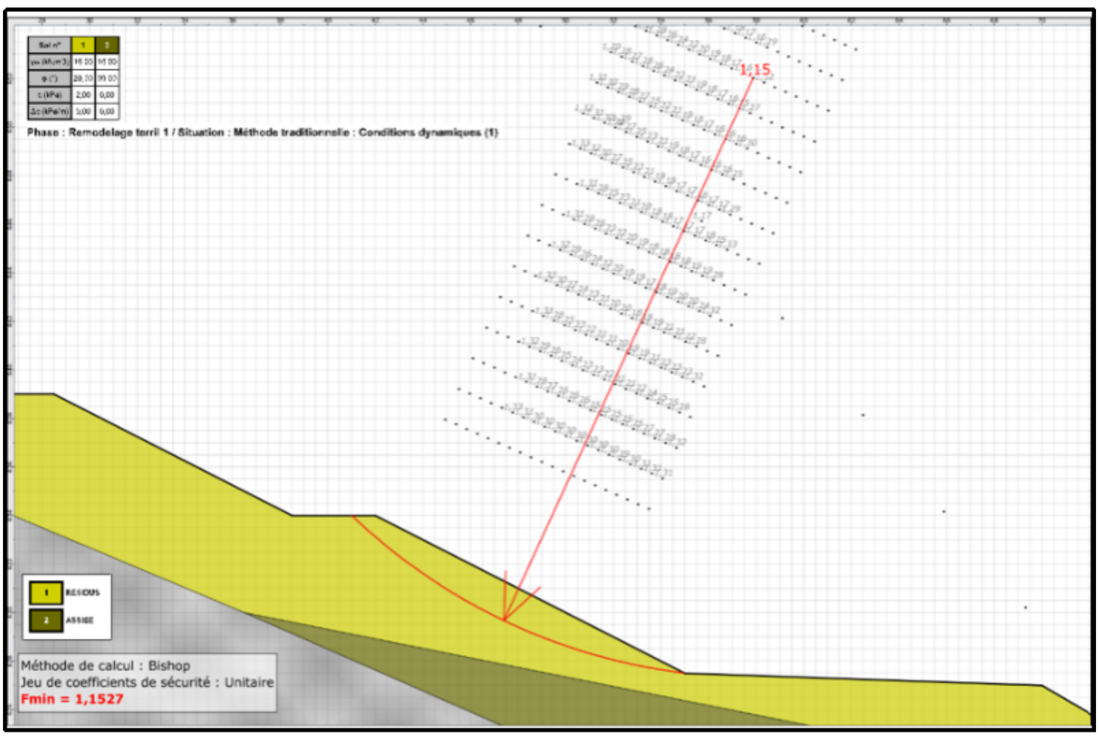

Figure 14. Stability results using traditional method, pseudo-static conditions (Section 02).

Note: Results of the stability analysis under dynamic conditions using the traditional approach, based on the Bishop method with unit safety coefficients. The minimum safety factor is F_{min} = 1.15.

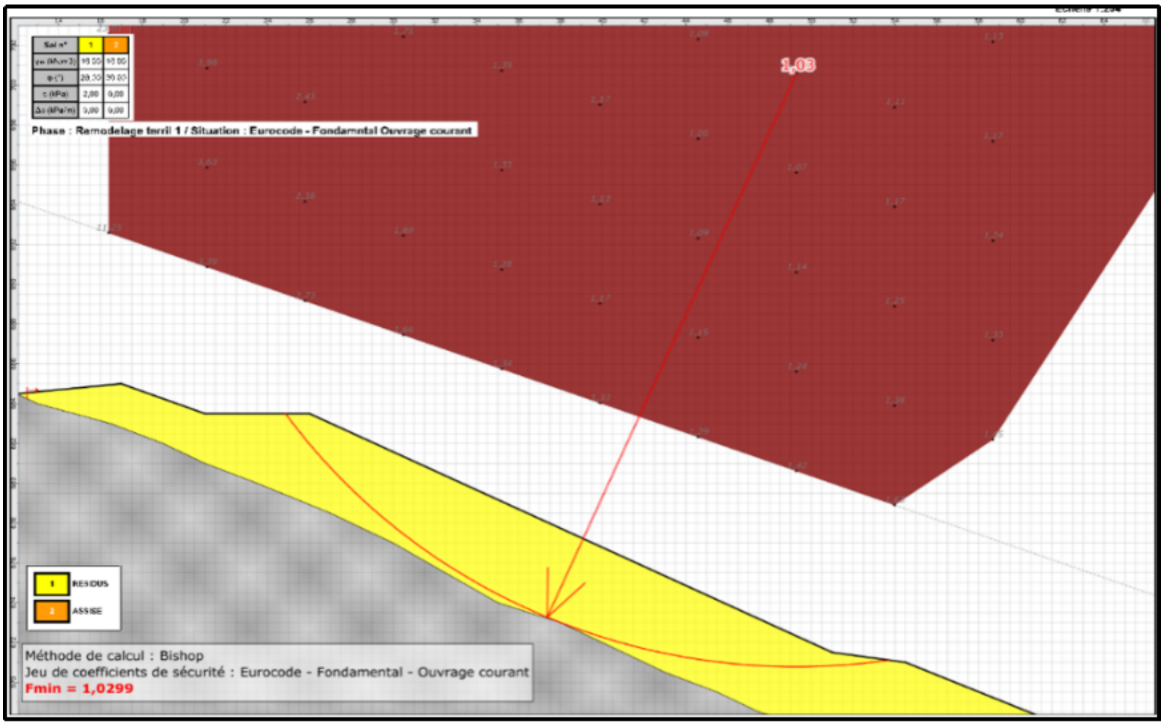

Figure 15. Stability result, Eurocode approach (Section 01).

Note: Results of the stability analysis under static conditions using the Eurocode approach (fundamental case–standard structure), based on the Bishop method with Eurocode safety coefficients. The minimum safety factor is F_{min} = 1.03.

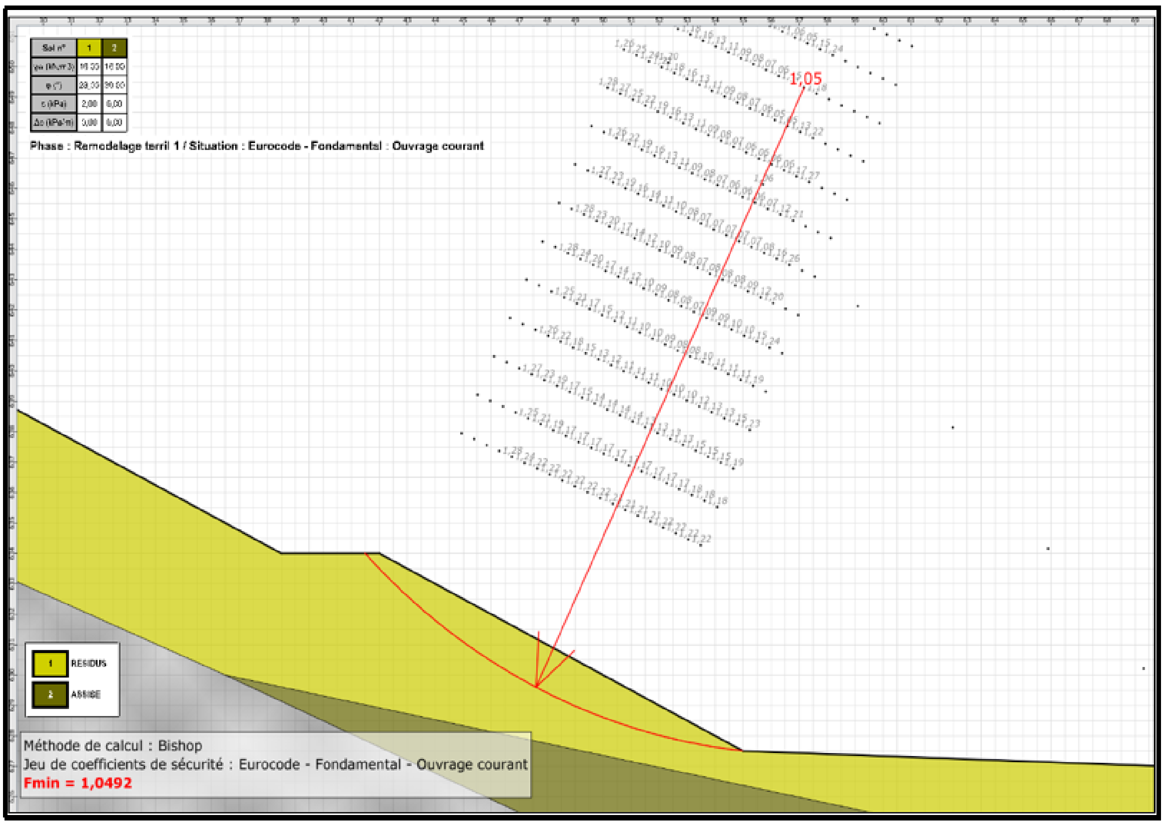

Figure 16. Stability result, Eurocodes approach (Section 02).

Note: Results of the stability analysis under static conditions using the Eurocode approach (fundamental case–standard structure), based on the Bishop method with Eurocode safety coefficients. The minimum safety factor is F_{min} = 1.05.

Table 5. Summary of safety factor results after earthworks.

Sections	Static Conditions		Pseudo-Static Conditions		Eurocodes	
	FS_{min}	Observation	FS_{min}	Observation	FS_{min}	Observation
Section 01	1.42	Stable	1.11	Stable	1.03	Stable
Section 02	1.44	Stable	1.15	Stable	1.05	Stable

4. Conclusion

The stability analysis of the Auzelles mining site highlighted the potential risks associated with the presence of mining residues, particularly due to their steep slopes of between 35° and 40°. Various analyses carried out using Talren V5 software and several standard approaches (traditional method and Eurocode 7) showed that the initial state of the site was unstable, with safety factors below the required thresholds. However, after earthworks to reduce the slopes to 27°, the safety factors all exceeded the recommended minimum thresholds: 1.3 in static, 1 in pseudo-static, and 1 according to the Eurocode approach. These results confirm that the proposed reprofiling interventions are effective in ensuring the long-term stability of the deposit and preventing any landslides that could lead to pollution of the Miodet. The stability of the slopes is therefore considered acceptable at the end of the planned work, subject to compliance with the adopted calculation assumptions.

In order to guarantee the long-term stability of the site and limit environmental risks, several measures are recommended. First, it is recommended that the slag heap be reshaped through earthworks (balanced excavation/backfill) in order to reduce the slopes and create berms. At the same time, water management structures must be integrated into this reshaping, such as drainage benches, ditches, and water outlets, to effectively channel runoff. It is also advisable to cover the entire slag heap with a mineral layer approximately 30 cm thick, consisting of topsoil brought in from outside. Finally, this cover should be vegetated to promote soil stabilization, limit erosion, and improve the environmental integration of the site.

Further research could focus on the impact of climate change (extreme rainfall, freeze/thaw cycles) on the stability of the tailings. It would also be relevant to study in more detail the effects of water content variation on the mechanical properties of the tailings. Finally, the use of advanced three-dimensional models and long-term geotechnical monitoring would provide a more detailed understanding of the behavior of the tailings pile over time.

Author Contributions

Conceptualization, D.S. and M.D.; methodology, D.S. and M.D.; software, M.D.; validation, D.S. and M.D.; formal analysis, D.S. and M.D.; investigation, M.D.; resources, D.S. and M.D.; data curation, D.S. and M.D.; writing—original draft preparation, D.S. and M.D.; writing—review and editing, M.D. and A.A.K.; visualization, M.D. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare they have no competing interests.

AI Use Statement

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

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